A global description of heavy-ion collisions

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Abstract. A model for the evolution of ultrarelativistic heavy-ion collisions at both CERN SPS and RHIC top energies is presented. Based on the assumption of thermalization and a parametrization of the space-time expansion of the produced matter, this model is able to describe a large set of observables including hadronic momentum spectra, correlations and abundancies, the emission of real photons, dilepton radiation and the suppression pattern of charmonia. Each of these obervables provides unique capabilities to study the reaction dynamics and taken together they form a strong and consistent picture of the evolving system. Based on the emission of hard photons measured at SPS, we argue that a strongly interacting, hot and dense system with temperatures above 250 MeV has to be created early in the reaction. Such a system is bound to be different from hadronic matter and likely to be a quark-gluon plasma, and we find that this assumption is in line with the subsequent evolution of the system that is reflected in other observables.

1. Introduction

Lattice simulations (e.g. [1]) predict that QCD undergoes a phase transformation at a temperature $T_C \approx 150 - 170$ MeV [2, 3] from a confined hadronic phase to a phase, the quark-gluon plasma (QGP), in which quarks and gluons constitute the relevant degrees of freedom and the chiral condensate vanishes. Experimentally, this prediction can only be tested in ultrarelativistic heavy-ion collisions. However, finding evidence, and ultimately proof, for the creation of a quark-gluon plasma faces several difficulties. Arguably the greatest challenge is to link experimental observables to quantities measured on the lattice.

For a large set of observables, the evolution of the expanding medium is a key ingredient for their theoretical description. It is also the place where results from lattice QCD fit in: assuming a thermalized system is created, its evolution is governed by the equation of state (EoS). Hence, in order to test the lattice QCD predictions, one has to start with this assumption and show that it leads to a good description of the experimental data. In the following, we will demonstrate that this is indeed possible by introducing a parametrized evolution model.

2. The model framework

Assuming that an equilibrated system is created a proper time of order 0.5-1 fm/c after the onset of the collision, we make the ansatz

$$s(\tau, \eta_s, r) = NR(r, \tau) \cdot H(\eta_s, \tau) \tag{1}$$

for the entropy density s at given proper time τ as measured in a frame co-moving with a given volume element, $\eta_s = \frac{1}{2}\ln(\frac{t+z}{t-z})$ the spacetime rapidity and $R(r, \tau), H(\eta_s, \tau)$ two functions describing the shape of the distribution and N a normalization factor. We use Woods-Saxon distributions

$$R(r, \tau) = 1/\left(1 + \exp\left[\frac{r - R_c(\tau)}{d_{ws}}\right]\right) \tag{2}$$

and

$$H(\eta_s, \tau) = 1/\left(1 + \exp\left[\frac{\eta_s - H_c(\tau)}{\eta_{ws}}\right]\right). \tag{3}$$

for the shapes. Thus, the ingredients of the model are the skin thickness parameters d_{ws} and η_{ws} and the parametrizations of the expansion of the spatial extensions $R_c(\tau), H_c(\tau)$ as a function of proper time. From the distribution of entropy density, the thermodynamics can be inferred via the EoS (as obtained in lattice calculations) and the particle emission function is then calculated using the Cooper-Frye formula for a freeze-out hypersurface characterized by a temperature T_F. The total entropy is an input parameter whereas the entropy density carried by the different hadronic degrees of freedom is calculated in a statistical hadronization framework. The model is described in greater detail in [4, 5].

An important feature of the model is that it does not require boost invariance but allows for an accelerated longitudinal expansion pattern instead with initial rapidity η_0 not equal to final rapidity η_f. This implies that in general the spacetime rapidity η_s at some point is not equal to the rapidity η, rather there's a non-trivial relation dependent on the trajectory leading to this point. In most relevant cases, however, the relation can be approximated by $\eta = const. \cdot \eta_s$ [4]. Such initial longitudinal compression and re-expansion implies longer lifetime and higher initial temperature and energy density as compared to a Bjorken scenario.

The adjustible parameters of the model are freeze-out temperature T_F, the radial expansion velocity $v_\perp$, the initial longitudinal expansion rapidity η_0 and the skin thickness parameters d_{ws}, η_{ws}.

3. Hadronic observables

In the following, we only focus on central collisions. The model parameters are fitted to the recent SPS data for 158 AGeV Pb-Pb collisions obtained by NA49 and CERES [6, 8] and 200 AGeV Au-Au collision data obtained by the PHENIX collaboration at RHIC [7, 9]. The data for both SPS and RHIC favour a comparatively low freeze-out

temperature of order 100-110 MeV and a strong transverse flow ($v_\perp = 0.57$ at SPS and 0.65 at RHIC). In both cases, the initial rapidity inverval is found to be significantly smaller than the finally observed rapidity interval η_f, we find $\eta_0 = 0.55$, $\eta_f = 1.45$ at SPS and $\eta_0 = 1.8, \eta_f = 3.6$ at RHIC. This is a crucial ingredient for the successful description of the data and the numbers indicate that the actual dynamics of the system could be very different from a Bjorken expansion. The resulting transverse mass (m_t) spectra for different hadron species and the pionic Hanbury-Brown Twiss (HBT) correlation radii show good agreement with the data (Figs. 1, 2 and 3).

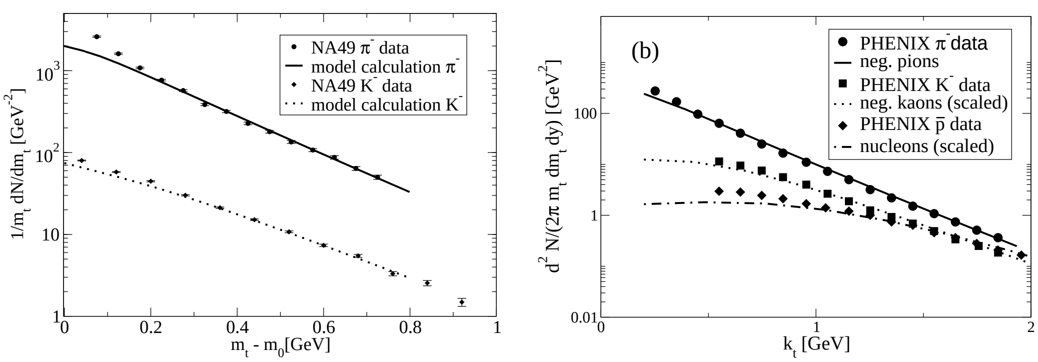

Figure 1. Transverse mass spectra obtained by NA49 [6] (left) and by PHENIX [7] (right) compared with model results. The model does not include contribution from resonance decays relevant at low transverse mass.

There is a contribution to the π^- m_t-spectra coming from the vacuum decay of resonances after kineitc decoupling at τ_f. The model is able to calculate the magnitude of this contribution using statistical hadronization but not its m_t distribution, therefore it is left out when we compare with data. This explains the mismatch at low m_t and that the integrated spectrum does not yield the multiplicity indicated by the data. The same is visible in the K^- spectra and the nucleon spectra, albeit less pronounced.

4. Electromagnetic observables

For the emission rate of direct photons, we use the complete $O(\alpha_s)$ calculation [10, 11, 12, 13, 14, 15, 16] in the form of the parameterization provided in [16]. The spectrum of emitted photons can be found by folding the rate [16] with the fireball evolution. In order to account for flow, the energy of a photon emitted with momentum $k^\mu = (k_t, \mathbf{k_t}, 0)$ has to be evaluated in the local rest frame of matter, giving rise to a product $k^\mu u_\mu$ with $u_\mu(\eta_s, r, \tau)$ the local flow profile. For comparison with the measured photon spectrum [17], we present the differential emission spectrum into the midrapidity slice $y = 0$. The resulting photon spectrum is shown in Fig. 4 (left). Details of the calculation can be found in [4, 18, 19].

The lepton pair emission rate from a hot domain populated by particles in thermal equilibrium at temperature T is proportional to the imaginary part of the spin-averaged

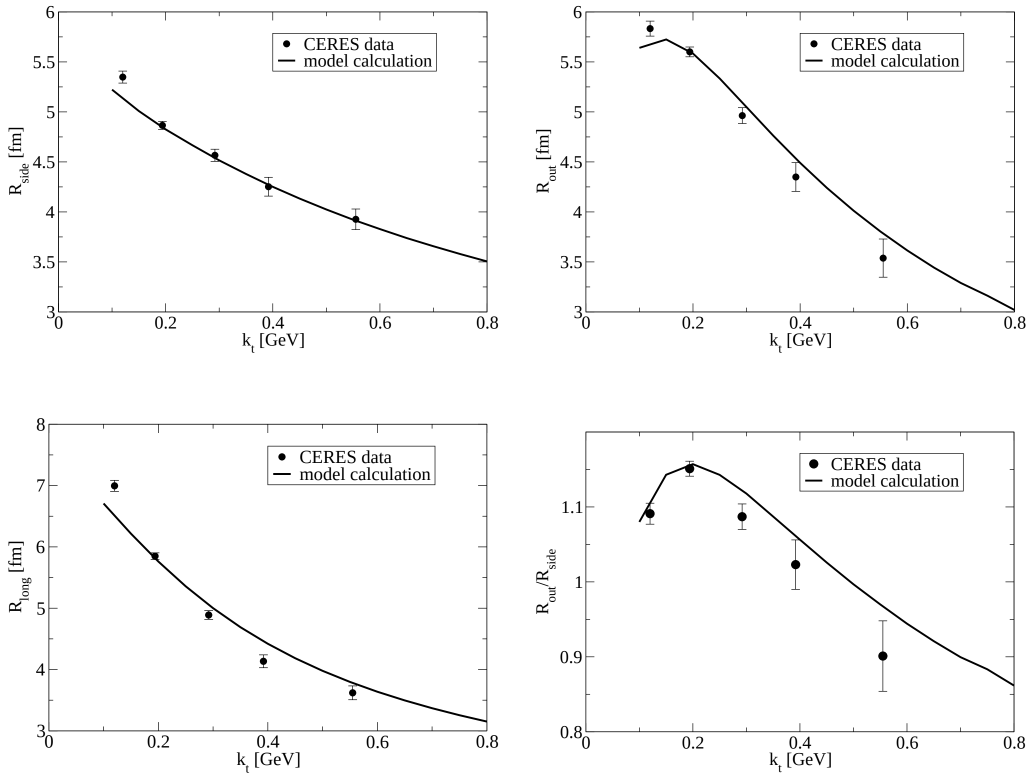

Figure 2. HBT Correlation radii obtained by the CERES collaboration [8] as a function of transverse pair momentum k_t compared with the model results. No systematic errors are included in the experimental errorbars.

photon self-energy, with these particles as intermediate states. The thermally excited particles annihilate to yield a time-like virtual photon with four-momentum q which decays subsequently into a lepton-antilepton pair. The information about the strong interaction dynamics is encoded in the spectral function which enters the emission rate. For its computation, we have to use different techniques for dealing with partonic and hadronic degrees of freedom. In the partonic phase, we use a leading order calculation using thermal quasiparticles as degrees of freedom. In the hadronic phase we calculate in two different approaches to estimate the theoretical uncertainty - a chiral model [21] and a mean-field model [22].

The resulting invariant mass spectrum agrees with the measured data for both the chiral model and the mean field model of hadronic matter. For SPS, we find photons in the momentum range between 2-3 GeV to be dominated by thermal emission from an initial high-temperature partonic phase whereas the dilepton yield in the invariant mass region below 1 GeV is dominated by emission from hadronic matter. Both quantities are sensitive to the 4-volume of radiating matter and complement each other in supporting the fireball evolution model in its different evolution phases. Most notably, the dilepton result indicates that hadronic matter does not cease to interact after the phase transition, instead substantial modifications of the ρ properties in medium are required by the data.

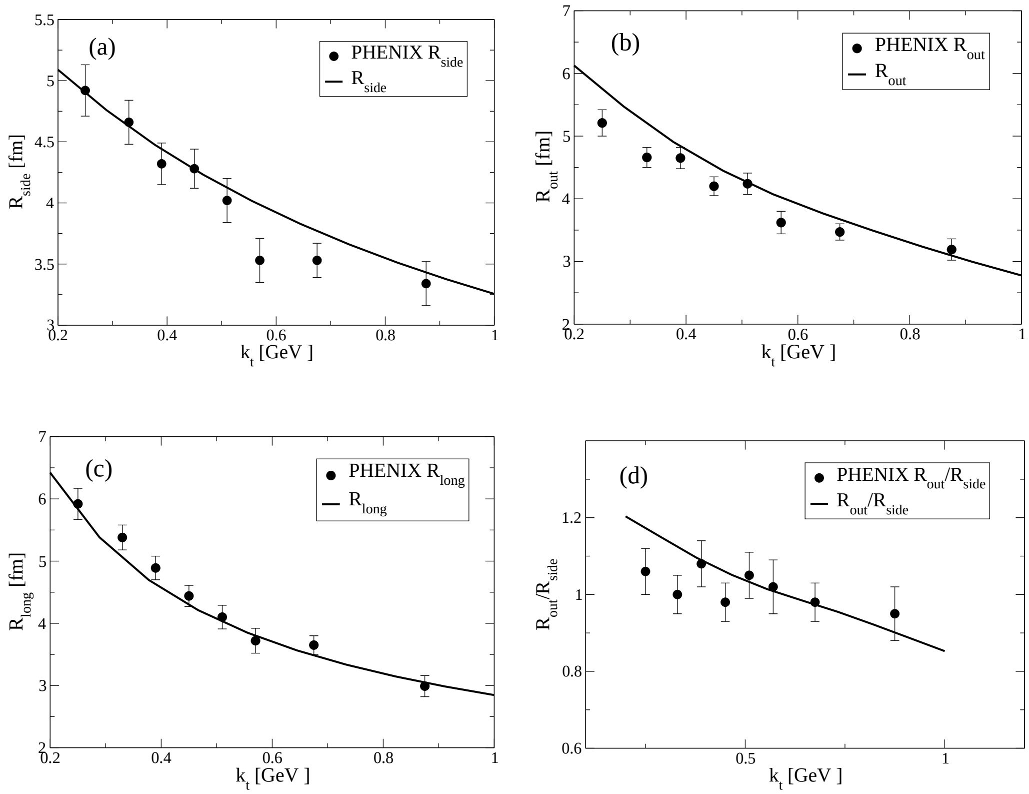

Figure 3. HBT Correlation radii obtained by the PHENIX collaboration [9] as a function of transverse pair momentum k_t compared with the model results.

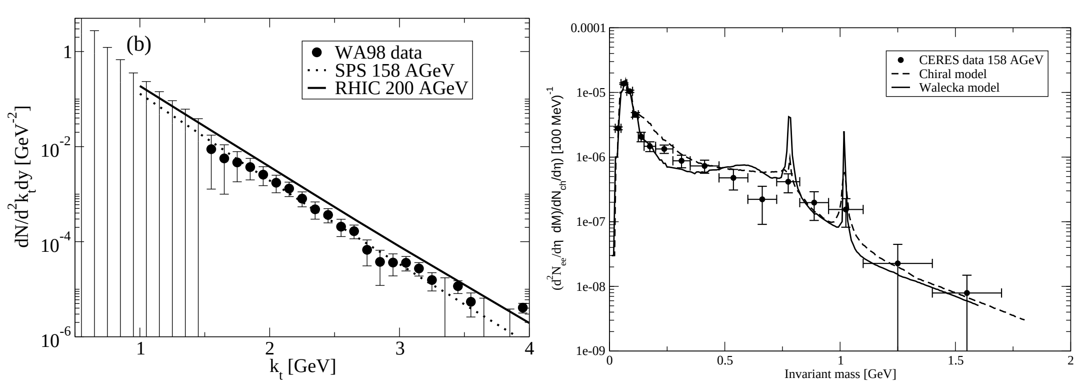

Figure 4. Left: The direct photon spectrum measured at the CERN SPS [17] as compared with the model calculations for SPS (dotted) and RHIC (solid). Right: The dilepton spectrum compared with SPS 158 Pb-Au results [20] (dots) using both the chiral model (dashed) and the mean field model (solid) spectral function.

The photon spectrum cannot be reproduced in a Bjorken expansion, thus confirming the findings outlined above based on an analysis of hadronic observables. The sensitivity of the yield to the equilibration time τ_0 allows to obtain $\tau_0 < 3$ fm/c [4, 18].

For RHIC, we find that the contribution to the photon spectrum coming from hadronic matter is as large as the yield from partonic matter due to the strong flow. This is unfortunate, as it reduces the capability of a photon measurement to help in the determination of the peak temperature reached in the collision [19]. In both calculations, a pre-equilibrium contribution to the photon yield is missing. Such a contribution is expected to be most relevant for the high momentum region and to dominate the yield above 3-4 GeV.

5. Charmonium

Charmonia yields are calculated by solving rate equations for the interaction of the state with the medium. The initial condition for the rate equations is determined by comparing to the production in p-p and p-A collisions. For SPS conditions, dissociation of the state dominates and we find the equation

$$\frac{d}{d\tau} N_\Psi^y(\tau) = -\lambda_D(\tau)\, N_\Psi^y(\tau)\,, \quad \lambda_D(\tau) = \sum_n \langle\langle\, \sigma_D^n\, v_{rel}\,\rangle\rangle(\tau)\ \rho_n(\tau) \tag{4}$$

for the rapidity density $N_\Psi^y(\tau)$ as a function of proper time τ where ρ_n is the medium density [4, 23]. Folding this equation with the fireball evolution yields Fig. 5.

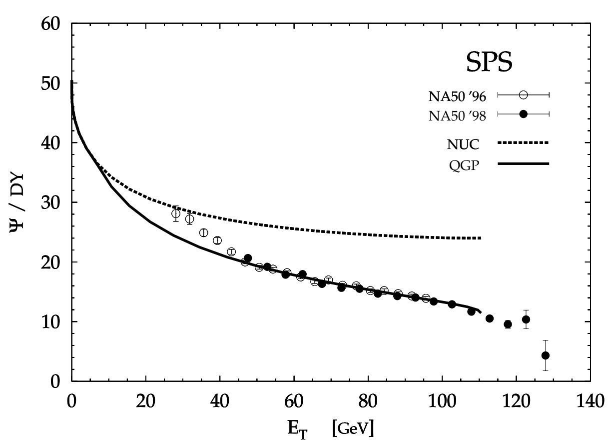

Figure 5. Result at SPS energy for the ratio Ψ/DY as function of the transverse energy. The dashed curve includes only nuclear effects, while the full line is the complete result including gluon dissociation.

We find good agreement with the data with the exception of the high E_T region where fluctuations in the transverse energy (not included in the model) are relavent and in the low E_T region where the system cannot be expected to be thermalized any more.

6. Summary

We have presented a thermal description of ultrarelativistic heavy-ion collisions at the CERN SPS for 158 AGeV Pb-Pb which is highly consistent and leads to a good

description of a large set of different observable quantities. While this does not provide a conclusive proof for the creation of a thermalized system (and hence a QGP), it constitutes certainly strong evidence for it. It remains to be investigated if the results can be reproduced in a thermal microscopical transport description (like hydrodynamics) and if a non-thermal framework is able to describe the experimental results as well or if thermalization is required by the data.

For RHIC, we have presented a fireball evolution model which is able to simultaneously describe both HBT correlations and transverse mass spectra. This parametrized evolution model will hopefully be able to guide hydrodynamical models (which currently fail to provide such a simultaneous description). We are now in the process of making predictions for other observables based on this evolution model.

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